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Precision tests of the Standard Model : Present status

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Abstract : Electroweak data from LEP and SLC as well as data from TEVATRON (CDF/D0) have established the credentials of the Glashow-Weinberg-Salam model (the so called Standard Model) at such a level that there is no other competitive model for the purpose of describing physics at the 100 GeV scale In this talk, I review the status of the Standard Model by comparing precision data with precision calculations.

Keywords : Standard model, LEP, Tevatron

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1. Introduction

During the 6 years (Summer 1989 – Summer 1995) of running on and around $\sqrt{s} \simeq m_Z$, the 4 experiments (ALEPH, OPAL, DELPHI and L3) of the Large Electron Positron Collider (LEP) at CERN have in total collected nearly 20 millon Z-events. The analyses of those data have led to an unquestionable superiority of the Standard Model (SM) over any others at ~100 GeV scale. Just immediately after LEP started running, the situation in August 1989, as regards the key quantities of interest, was the following [1] : m_Z = 91.120(160) GeV, m_t = 130(50) GeV, $\sin^2\theta_{\rm eff}$ = 0.23300(230) and $\alpha_S(m_Z)$ = 0.110(10). Their present values are [2] : m_Z = 91.1867(20) GeV, m_t = 173(5) GeV (including CDF/D0), $\sin^2\theta_{\rm eff}$ = 0.23152(23) (LEP + SLD Average) and $\alpha_S(m_Z)$ = 0.119(4) (World Average). The progress is overwhelming! Remarkable is the fact that the measurement uncertainties of the electroweak observables have now been brought down to *per mille* level [3]. The CDF and D0 Collaborations of the Fermilab $p\bar{p}$ collider TEVATRON have in the mean time succeeded in finding the top quark [4]. The targets of these machines, when they started, were : (i) perform precision tests of the SM at a few *per mille* accuracy, (ii) count the number of light generations, (iii) search for the top quark, (iv) search for the Higgs and

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(v) look for new resonances (if we were very lucky!). Although the first three objectives have been successfully met (a fourth light neutrino is now 91σ away!), the Higgs boson still eludes detection and no new resonances have been found. The theoretical uncertainties are at present at the same level. The theoretical uncertainties in the SM, for given m_t, m_H and $\alpha_s(m_Z)$, stem mainly from the uncertainties associated with the hadronic contribution to the photon vacuum polarization [$\alpha^{-1}(m_Z) = \alpha^{-1}(0)\ (1-\delta\alpha) = 128.89 \pm 0.09$, where the evaluation of the light quark content yields $\delta\alpha(\text{had}) = 0.0280 \pm 0.0007$ [5]], which is included in the RG running of the electromagnetic fine-structure constant $\alpha(0) \to \alpha(m_Z)$. This propagates as a *per mille* error in the final predictions. Full one-loop and leading two-loop corrections are now available, but neglecting higher order effects manifest mildly through renormalization scheme dependence. Genuine weak loop effects ($O(G_F m_t^2)$) are now tested at the 5σ level and the present precision is high enough to sense the quantum corrections of the Higgs boson mass.

2. Physics at LEP

2.1. *Principal observables* :

During 1989-95 LEP has operated on and around the Z-peak with an integrated luminosity of 160 pb^{-1} and there is a collection of ~5 million visible Z-decay events per experiment. The principal measurements at LEP have been :

- Cross section $\sigma(e^+e^- \to f\bar{f})$ *vs* $\sqrt{s}$ (where $\sqrt{s} \approx m_Z$ and a few Γ_Z around m_Z). The peak cross section is given by $\sigma_f^0 = (12\pi\Gamma_e\Gamma_f / m_Z^2\Gamma_Z^2)$, where Γ_e and Γ_f are partial widths of the Z in the channels e and f and Γ_Z is the total width (half width at half maxima at the Breit-Wigner resonance).
- Partial widths $\Gamma_f \equiv \Gamma(Z \to f\bar{f}) = G_\mu m_Z^3 N_c^f (v_f^2 + a_f^2)(1 + 3\alpha Q_f^2/4\pi)/6\pi\sqrt{2}$, where the vector and axial vector couplings of the Z to the fermion f are given by $v_f = \sqrt{\rho}(t_3^f - 2Q_f \sin^2\theta_{\text{eff}})$ and $a_f = \sqrt{\rho}t_3^f$; $N_c^f = 1$ for leptons and $N_c^f = 3(1 + \alpha_S(m_Z)/\pi + \ldots)$ for quarks. The couplings have been dressed with improved Born-approximations : their meaning, particularly the implication of ρ-parameter and how and why the effective weak angle (θ_{eff}) differs from its tree level value, will be clear shortly.
- Forward-backward asymmetry $A_{FB}^f \equiv (\sigma_F - \sigma_B)/(\sigma_F + \sigma_B) \simeq 3A_e A_f/4$, where the suffixes F and B correspond to the forward and backward hemispheres, and $A_f = 2v_f a_f/(v_f^2 + a_f^2)$. In a purely parity-conserving interaction, the number of particles thrown in the forward and backward hemispheres would have been the same; a non-zero A_{FB}^f indicates an interference between the vector and axial vector couplings.
- Average τ-polarization $P_\tau \simeq -A_\tau$.

In SLC (the SLAC Linear e^+e^- Collider operating on the Z-peak with a total luminosity of 5 pb^{-1} upto 1996 and with an average electron polarization of 80%), observables related to polarized beam are :

- Left-right asymmetry $A_{LR} \equiv (\sigma_L - \sigma_R)/(\sigma_L + \sigma_R) \simeq -A_e$.
- Left-right forward-backward asymmetry $A^f_{LR} \simeq -3A_f/4$.

2.2. Renormalization procedure and radiative corrections :

To have a feeling why radiative corrections became necessary not long after LEP started running, let us look back to the situation in Summer 1992 [6] : the measured $v_l^{\rm exp} = -0.0362^{+0.0035}_{-0.0032}$, when compared with its tree level SM prediction $v_l^{(\rm SM,tree)} = -0.5 + 2\sin^2\theta_W = -0.076$ ($\sin^2\theta_W$ obtained from $G_\mu = \pi\alpha(0)/\sqrt{2}m_Z^2 \sin^2\theta_W \cos^2\theta_W$), showed a 13σ discrepancy, inevitably calling for the necessity of dressing the Born-level prediction with radiative corrections. However, just the consideration of running $\alpha(0) \to \alpha(m_Z)$ and extracting $\sin^2\theta$ (to replace $\sin^2\theta_W$ in the expression of v_l) from $\cos^2\theta \sin^2\theta = \pi\alpha(m_Z)/\sqrt{2}G_\mu m_Z^2$, enabled one to obtain $v_l = -0.037$, *i.e.* within 1σ of its experimental value at that period. The essential point is that it was possible to establish a significant consistency between data and predictions just by considering the running of α and it was only much later, with a significantly more data, that the weak loop effects were felt. To understand the essential features of the renormalization procedure, let us follow the on-shell scheme and the readers are referred to two excellent reports [7,8] for details. The steps are the following : (i) write the bare Lagrangian and scale the fields and coupling constants by some constant *a priori* arbitrary parameters called 'the renormalization constants' (these are usually denoted by z and $\phi_i \to \sqrt{z_1^i}\,\phi_i$ and $g_j \to z_2^j g_j$ respectively); (ii) select renormalization input parameters—usually these are the best measured experimental quantities—in this case,

- $\alpha^{-1}(0) = 137.0359895(61)$,
- $G_\mu = 1.16639(2) \times 10^{-5}\,{\rm GeV}^{-2}$,
- $m_Z = 91.1867 \pm 0.0020$ GeV;

(iii) impose renormalization conditions (see below) and (iv) extract those effects that cannot be absorbed during renormalization—these parametrize the effects of radiative corrections. The renormalization conditions are :

- The masses are defined as the pole positions of the corresponding propagators. Thus for a vector boson $V(W, Z\gamma)$, $\hat\Sigma_{VV}(m_V^2) = 0$, where $\hat\Sigma_{VV'}$ denotes a renormalized two-point (self-energy) function between V and V'.
- The residue of the photon propagator at $q^2 = 0$ is unity (QED demands it), *i.e.* $\hat\Sigma'_{\gamma\gamma} = 0$, where a prime on a $\hat\Sigma$ denotes its derivative w.r.t. q^2.
- There is no photon-Z mixing at $q^2 = 0$, *i.e.* $\hat\Sigma_{\gamma Z}(q^2 = 0) = 0$ (QED is thus not contaminated by Z).
- The photon-electron-electron vertex at $q^2 = 0$ with electrons in their mass shell is $ie\gamma_\mu$.

All the renormalization constants have by now been used. The net effects of renormalization then manifest through :

- $\alpha(q^2) = \alpha(0) \big/ (1 + \mathrm{Re}\,\hat{\Sigma}'_{\gamma\gamma}(q^2))$: this way $\alpha(0) \simeq (137.0)^{-1} \rightarrow \alpha(m_Z^2) \simeq (128.9)^{-1}$.
- Residue of the Z propagator at the Z-pole is *not* unity $\left(\hat{\Sigma}'_{ZZ}(q^2 = m_Z^2) \neq 0\right)$ and this gives rise to a non-trivial wave function renormalization on an on-shell Z (decaying to $f\bar{f}$) line. This leads to the *celebrated ρ-parameter* : $\rho = (1 - \Delta r) / (1 + \hat{\Sigma}'_{ZZ}(m_Z^2))$, where the muon decay radiative correction Δr (which is indeed a charged-current radiative correction) enters into the game when we use G_μ, obtained from μ-decay, in the neutral current decay (Z decay) formula.
- Non-zero photon-Z mixing at $q^2 = m_Z^2$ (*i.e.* $\hat{\Sigma}_{\gamma Z}(q^2 = m_Z^2) \neq 0$). This modifies $\sin^2\theta_W$ to $\sin^2\theta_{\rm eff}$.

2.3. *Parametrization of radiative corrections* :

2.3.1. *Oblique parameters* :

We should first note that not all renormalization constants could be absorbed in the redefinition of parameters. Those unabsorbed ones cast observable impact. We first concentrate on *universal corrections, i.e.* those which originate from the renormalization of vector boson two-point functions and thus do not depend on external fermion lines. How many independent parameters carry the observable effects ? Essentially there are four types of two-point functions, namely, $\Sigma_{\gamma\gamma}(q^2)$, $\Sigma_{\gamma Z}(q^2)$, $\Sigma_{ZZ}(q^2)$ and $\Sigma_{WW}(q^2)$. There are 2 relevant energy scales at which measurements are made : $q^2 = 0$ and $q^2 = m_Z^2$. Hence there are eight such parameters. QED demands (see the renormalization conditions) : $\Sigma_{\gamma\gamma}(0) = 0$ and $\Sigma_{\gamma Z}(0) = 0$. Out of the other six, three are absorbed in the renormalization of the input parameters α, G_μ and m_Z. Hence the remaining three (in fact three linearly independent combinations of those two-point functions) will have observable effects. These are usually parametrized by S, T and U, the so called 'oblique parameters', defined below [9][1] :

- $S = 16\pi m_Z^{-2}\left[\Sigma_{3Y}(0) - \Sigma_{3Y}(m_Z^2)\right]$,
- $T = 4\pi m_Z^{-2}\left[\Sigma_{11}(0) - \Sigma_{33}(0)\right] / \sin^2\theta_{\rm eff}\cos^2\theta_{\rm eff}$,
- $U = 16\pi m_W^{-2}\left[\Sigma_{11}(m_W^2) - \Sigma_{11}(0)\right] - 16\pi m_Z^{-2}\left[\Sigma_{33}(m_Z^2) - \Sigma_{33}(0)\right]$.

In the above definitions, I have used the $\{1, 2, 3, Y\}$ basis of the SU(2) ⊗ U(1) gauge theory rather than the $\{\gamma, Z, W^\pm\}$ basis. The T parameter is related to ρ by $\Delta\rho \equiv \rho - 1 = \alpha T$. The

[1] I have adapted the definitions used by Bhattacharyya, Banerjee and Roy in [9]. A linear q^2-expansion of the form $\hat{\Sigma}(q^2) = \hat{\Sigma}(0) + q^2\hat{\Sigma}'(0)$ yields the definitions in Peskin and Takeuchi [9]. All these definitions assume the vacuum polarization dominance of radiative corrections. A slightly more general parametrization, using the ε_i variables, has been used by Altarelli and Barbieri [9].

leading SM contribution to $\Delta\rho$ is quadratic in top mass and logarithmic in Higgs mass and is given by [10] :

$$T^{\mathrm{SM}} \sim \left[(m_t^2/m_Z^2)-(m_Z^2-m_W^2)\ln(m_H^2/m_W^2)\right]/\pi.$$

At this point, it is worth pointing why T^{SM} is quadratic in m_t. The effect, as is evident from the definition of T, is generated by self-energies of massive vector bosons. Since the longitudinal components of those gauge bosons are essentially Higgs scalars, each vertex of a self-energy diagram (with top-quark floating inside the loop) picks up one power of m_t and hence the quadratic dependence. The Higgs mass appears logarithmically due to Veltman screening'. The parameter T, as matter of fact, captures the effect of custodial SU(2)' breaking. To appreciate this point, let us consider the SM scalar potential $V(\phi) = -m^2(\phi^\dagger\phi)+\lambda(\phi^\dagger\phi)^2/6$. Before the spontaneous symmetry breaking, there is a global O(4) symmetry in the potential which is broken to O(3) once the symmetry is broken in one direction. This O(3) is equivalent to a global SU(2) which we call 'custodial SU(2)'. It is precisely because of this custodial SU(2) that even after spontaneous symmetry breaking $m_{W_1}=m_{W_2}=m_{W_3}$. Once we apply this global symmetry to the Yukawa sector as well, we realise that this custodial SU(2) is broken by (i) fermion mass splitting in a weak doublet (this effect is quadratic and m_t naturally dominates) and (ii) hypercharge mixing (proportional to $(m_Z^2-m_W^2)$ that multiplies ln m_H). $\Delta\rho$ also parametrizes the quantum correction in photon-Z mixing at $q^2=m_Z^2$ in the following way :

- $$\sin^2\theta_{\mathrm{eff}} = \sin^2\theta - \frac{\cos^2\theta_W\sin^2\theta_W}{\cos^2\theta_W-\sin^2\theta_W}\cdot\Delta\rho,$$

where $\sin^2\theta$ is determined through $\cos^2\theta\sin^2\theta = \pi\alpha(m_Z)/\sqrt{2}G_\mu m_Z^2$

S and U are sensitive only to logarithmic effects and their SM expressions are not displayed. It is worth noting that S is sensitive to *non-decoupling* physics. Even a degenerate chiral fermion generation (which does not contribute to T), even in the infinite mass limit, contributes to S and its contribution is estimated to be

$$S^{\mathrm{deg\,gen.}} = N_c\,\Sigma_i\left(t_{3L}^i-t_{3R}^i\right)^2/3\pi,$$

where N_c is colour and $t_{3L,R}^i$ corresponds to the third component of the weak isospin of the left- and right-handed component of the fermion i. The contribution of a heavy degenerate 4th generation or a mirror family is $2/3\pi \approx 0.21$ and the fitted value of the new physics contribution to S $\left(S^{\mathrm{new}} = -0.19 \pm 0.16^{-0.08}_{+0.17}\ [11]\right)$ allows not more than one such generation at 2σ. QCD-like Technicolour models generally yield large positive S and are excluded [9]. However, the walking Technicolour models survive as they contribute to S only by small amount (even negatively) [12].

2.3.2. *$Zb\bar{b}$-vertex correction* :

Non-universal vertex corrections are generally not important *except* in one situation, namely, the $Zb\bar{b}$-vertex correction. The W-boson and top-quark mediated triangle graphs induce a sizable correction to the $Zb\bar{b}$-vertex. Since the contribution comes from a chiral fermion inside the loop, it is non-decoupling and since the longitudinal W couples to a fermion with a strength proportional to its mass, the effect is quadratic in m_t. Moreover, there is no CKM suppression as $V_{tb} \simeq 1$. The effect is parametrized by a shift of the vector and axial couplings of Z with b-quark compared to those with d-quark :

- $v_b(a_b) = v_d(a_d) - 19\Delta V_b^t/60$, where
- $\Delta V_b^t \simeq -(\alpha/\pi)\left[m_t^2/m_Z^2 + (13/6)\ln(m_t^2/m_Z^2)\right]$.

A noteworthy point is that ΔV_b^t, on account of its negligible m_H-dependence, allows an indirect measurement of m_t without any need of specifying m_H (not so is the situation with $\Delta\rho$!).

2.4. *R_b-R_c-$\alpha_S(m_Z)$ Crisis! Is it over ?*

When most of the measurements at LEP were agreeing so well (perhaps too well!!) with their SM predictions, $R_b (\equiv \Gamma_b/\Gamma_{\rm had})$ continued to stay a few sigma above and $R_c (\equiv \Gamma_c/\Gamma_{\rm had})$ a few sigma below from their respective SM predictions. The fact that all 4 LEP-groups were reporting the same trend amused the physics community for more than a year leading to lots of speculations (sometimes wild!) for physics beyond the SM. First we note that for m_t = 180 GeV, $R_b^{\rm SM} = 0.2158$ and $R_c^{\rm SM} = 0.172$. The experimental values reported at Beijing 1995 [13] were :

- $R_b^{\rm exp} = 0.2219 \pm 0.0017$ (3.7σ above SM!),
- $R_c^{\rm exp} = 0.1543 \pm 0.0074$ (2.5σ below SM!).

In fact, the crisis was just not a $R_b - R_c$ crisis, it was rather a R_b-R_c-$\alpha_S(m_Z)$ crisis! Strictly speaking, there was an α_S anomaly too—while $\alpha_S(m_Z)$ from LEP was pointing towards a central value 0.120, its measurement from scaling violation in deep inelastic scattering was showing a central value 0.112 (although these two measurements had an overlap within 1σ). Notice that at LEP, one way to measure $\alpha_S(m_Z)$ is from

- $R_l = (\Gamma_{\rm had}/\Gamma_l) = (\Gamma_{\rm had}^{\rm weak}/\Gamma_l)\left[1 + \alpha_S(m_Z)/\pi + \cdots\right]$,

where $\Gamma_{\rm had}^{\rm weak}$ is the weak part of the hadronic width. Notice that if one could add a few MeV to $\Gamma_b^{\rm weak}$ (due to a possible positive interference from some new physics contributing to b-quark partial width), one would not only push up the theoretical prediction for R_b, making it more comfortable with data, $\alpha_S(m_Z)$ measured the above way would be drifted down closer to the value obtained from scaling violation. Thus 'R_b–$\alpha_S(m_Z)$' part of the crisis could, in principle, be solved in one stroke! However, as I mentioned before, it was a three-prong crisis, and any attempt to subtract out the required MeV from $\Gamma_c^{\rm weak}$ to solve the R_c problem, could only push $\alpha_S(m_Z)$ further away from that obtained from scaling violation. How reliable were those data ? Did they survive the test of time ? No! The situation took a dramatic turn in Warsaw 1996. The reported numbers there [14] :

$R_b^{\rm exp}$ = 0.2179 ± 0.0012 (1.8σ above SM!) and

$R_c^{\rm exp}$ = 0.1715 ± 0.0056 (on the dot!!!),

not only amused even more, but puzzled the community this time as to how all 4 LEP Collaborations could simultaneously change their numbers in the same directions and that too by such a large extent! What happened ?

2.4.1 *What happened to R_c ?*

The data allow a direct measurement of $(\Gamma_c/\Gamma_{\rm had})P(c \to X_c){\rm Br}(X_c)$, where X_c is a charmed hadron ($D^0, D^\pm, \ldots; D^0 \to K^-\pi^+, \ldots$). R_c has gone *up* because [15,16] :

- More data have been included.
- Decrease in Br ($D^0 \to K\,\pi^+$) from (4.01 ± 0.14)% to (3.83 ± 0.12)% (ARGUS input).
- Decrease in $P(g \to c\bar{c})$, which is a backgound.
- New techniques have been employed (*e.g.* "slow pion tag") at LEP to measure $P(c \to D^{*+})$ Br ($D^{*+} \to \pi^+ D^0$) and this has also gone down.

2.4.2 *What happened to R_b ?*

R_b has gone *down* mainly because [15,16] :

- More data have been included.
- Primary vertex for each event has been reconstructed seperately in two hemispheres leading to small hemisphere correlations (ALEPH).
- Better understanding of the charm sector has been made possible.
- Several mutually exclusive tags have been used, which reduces the systematic errors.

Also the α_S-anomaly had gone away at the same time. The different measurements of $\alpha_S(m_Z)$ have now come to a much better agreement than before.

The present experimental situation is the following [2] :

- $R_b^{\rm exp}$ = 0.2170 ± 0.0009,
- $R_c^{\rm exp}$ = 0.1734 ± 0.0048,
- $\alpha_S(m_Z)$ = 0.119 ± 0.004.

The conclusion is : *Yes, the R_b-R_c-$\alpha_S(m_Z)$ crisis seems to be over !*

3. Summary

Here I list the main results :

- Number of light neutrinos = $N_\nu \equiv \Gamma_{\rm inv} / \Gamma_\nu^{\rm SM} = (\Gamma_{\rm inv} / \Gamma_l)(\Gamma_l / \Gamma_\nu)^{\rm SM}$ = 2.993 ± 0.011. Indeed Γ_ν is an SM input in this determination. Splitting the ratio of partial widths into two such factors (as shown) reduces the theoretical uncertainties. A fourth light neutrino is ruled out by 91σ!
- The mass of the Z-boson, $m_Z = 91.1867 \pm 0.0020$ GeV, has been measured with a precision $\sim 2 \times 10^{-5}$.
- The world average of the top mass m_t is 173.1 ± 5.4 GeV (Direct search at TEVATRON dominates).
- Fitted value (LEP) of $m_H = 115^{+116}_{-66}$ GeV, which implies $m_H \leq 420$ GeV (95% CL).
- The world average of the W-mass is given by, $m_W = 80.43 \pm 0.08$ GeV. By the end of LEP2 and TEVATRON Run 2, the error is expected to be reduced to 30–40 MeV.
- Partial widths of z are measured at a *per mille* level. The forward-backward asymmetries are measured at a few *per cent* level.
- The effective weak mixing angle has been measured to a great accuracy :

  $\sin^2 \theta_{\rm eff}({\rm LEP}) = 0.23199 \pm 0.00028$ and $\sin^2 \theta_{\rm eff}({\rm SLD}) = 0.23055 \pm 0.00041$

  These should be compared with $\sin^2 \theta_{\rm eff}^{\rm SM} = 0.23157$.
- Number of extra heavy chiral generation could almost be one (from S-parameter)

My conclusion : *Order reigns in electroweak physics !*

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